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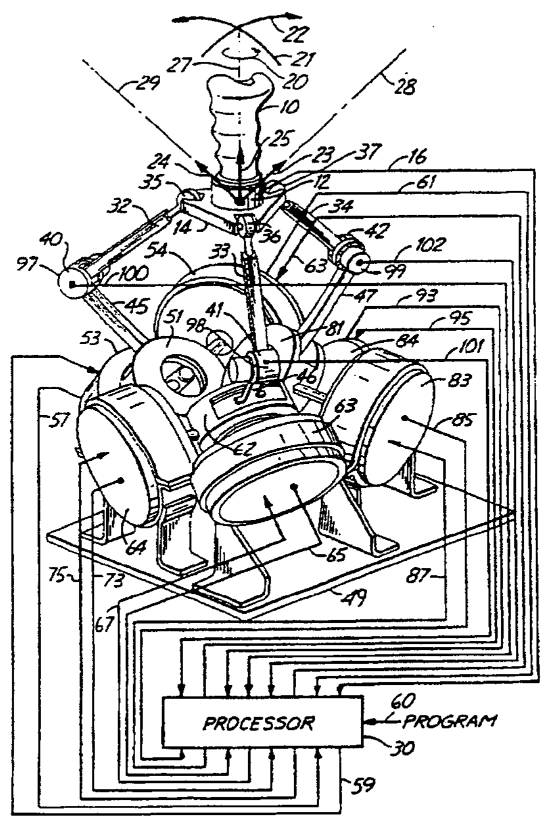
(54) Title: SECOND GENERATION SIX-DEGREE-OF-FREEDOM VIRTUAL PIVOT HAND CONTROLLER

(57) Abstract

A six-degree-of-freedom hand controller in which motions along six axes are resisted by motors (53-54, 63-64, 83-84) and in which the motors are arranged so as not to be required to carry the mass of another motor and to provide the proper "feel" for the motion of the hand grip (10) is provided.



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SECOND GENERATION SIX-DEGREE-OF-FREEDOM VIRTUAL PIVOT HAND CONTROLLER

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to hand controllers and more particularly to hand operated devices for operating remote systems such as flight control systems in aircraft or spacecraft or for controlling robotics or land vehicle mechanism and to provide desired power assistance and "feel" to the control.

2. Description of the Prior Art

Hand controllers are well known in the art as, for example, the virtual pivot hand controller of U.S. Patent 4,962,448 to Joseph DeMaio et al., issued October 9, 1990, and assigned to the assignor of the present invention. Six-degree-of-freedom mechanisms are also known in the art as, for example, the six-degree-of-freedom hand controller of Patent 4,914,976 issued April 10, 1990 to Charles E. Wyllie and the six-degree virtual pivot controller of patent application Serial No. 07/636,318 filed December 31, 1990 in the name of Jon M. Blomberg et al. assigned to the assignee of the present invention. Another device known as a Stewart platform has been modified to consist of a hand grip mounted on a platform which is connected at spaced locations to one end of three articulated legs while the other end of each leg is connected to be "actuated." The difficulty encountered in the modified Stewart platform is that if one attempted to use it for a realistic type hand controller such as shown in the Wyllie Patent, the forces felt by the operator as he moves the hand grip in various directions would not be realistic. For example, if the other end of the articulated legs were mounted for actuation with a pair of scissor springs to increase the force feedback as the legs move, which is common in the art as described in the copending application of Israel Menahem, Serial No. 07/655,740 filed February 14, 1992 or the mechanism shown in the copending application of Israel Menahem et al., Serial No. 07/738,255 filed July 30, 1991, both assigned to the assigner of the present invention most motion would be opposed by a complicated combination of spring forces. In fact, regardless of the actuator, motion of the hand grip would, in most cases, bring into play various combinations of opposing forces which would make obtaining the proper "feel" of the hand grip substantially impossible. Furthermore, actuating of the other ends of the articulated legs by some sort of motive means introduces complex dynamic and kinematic equations of motion that make it extremely difficult to generate motions of the hand grip that would reflect the desires of the operator.

SUMMARY OF THE INVENTION

The present invention operates with a mechanical arrangement similar to the modified Stewart platform but connects each of the three articulated legs to a special motor/pickoff combination such as has been described in the copending patent applications of Robert E. DeMers, Serial No. 07/824,632 and 07/824,633 both filed January 23, 1992 and assigned to the Assignee of the present invention. These motor/pickoffs operate to provide an output arm with the capability of rotating around two mutually orthogonal axes. The three motor/pickoffs are such that no motor is required to move the mass of another motor. This accordingly operates to minimize the inertia of the system. The hand grip is connected to a six-axis force/torque sensing device which produces signals indicative of forces and torques being applied in any of the six directions at the sensor location. The processor modifies them to transform them into values which would have been sensed at a "virtual pivot" (e.g., wrist joint) or at any fixed point relative to the base plate other than the sensor mounting location. These signals are a processor which operates to determine which of the motors should be activated and how much resistive force should be applied in order to move the hand grip with the proper "feel" in the direction indicated by the sensor. Motor control systems in the processor drive the motors in the proper directions and feedback from various sensors in the system provides information to the processor which tells it how the position of the hand grip continue to differ from the desired position. The reverse force which is applied may be customized to an individual's desires so that each operator will have the proper "feel" according to his particular liking. Accordingly the operator may have a customized hand grip, without altering the mechanical components, to able him to move the hand controller as he chooses with a "feel" that is best for his specific tastes.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a perspective and partly schematic view of the six-degree-of-freedom hand controller of the present invention.

Figure 2 shows a graph of the displacement of the hand controller and the corresponding resistive force or torque necessary to provide the realistic "feel."

Figure 3 shows a block diagram of the processor and its internal and external components.

Figure 4a, b and c shown the angles, and forces used in analyzing the kinematics and dynamics of the present invention.

Figure 5 shows the geometry of one of the articulated legs of the present

invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In Figure 1 a hand grip 10 is shown mounted on a force/torque sensor 12 which is mounted on a more or less triangular plate 14. Force/torque sensor 12 may be of the type sold by Assurance Technologies, Inc. as the ATI F/T Sensor and operates to produce a plurality of output signals on an output identified by reference numeral 16 whenever any forces and torques are applied to the hand grip in any of the six directions shown by arrows 20, 21, 22, 23, 24 and 25. Arrow 20 represents yaw motion about an axis shown as dash-dot line 27, arrow 21 represents roll motion about an axis shown as dash-dot line 28, arrow 22 represents pitch motion about an axis shown as dash-dot line 29, arrow 23 represents forward/backward motion along axis 28, arrow 24 represents right/left motion along axis 29, and arrow 25 represents up/down motion along axis 27. The signals indicative of the forces and torques applied by the operator in one or more of these directions are presented by output 16 to a processor 30 which determines from them which directions the operator desires the hand grip 10 to move.

Triangular platform 14 forms one part of a Stewart platform the rest of which comprises three, articulated legs having upper leg portions 32, 33 and 34, respectively, connected by rod end bearing connections 35, 36 and 37, respectively, to the corners of the triangular plate 14. Upper leg portions 32, 33 and 34 are pivoted at connections 40, 41 and 42 respectively to lower leg portions 45, 46 and 47 which extend downwardly at a angle from upper leg portions 32, 33 and 34 respectively and are connected to a base plate 49.

We have discovered that if the lower leg portions 45, 46 and 47 are connected to the base plate 49 by couplings such as are described in the above referred to DeMers copending applications, so that each leg is able to move in two mutually orthogonal directions, then it is possible to obtain all six directions of motion as shown by arrows 20, 21, 22, 23, 24 and 25 as desired. Furthermore, by controlling the speed of operation of the motors, the desired "feel" can be generated.

Lower leg portion 45 is shown connected to a first coupling 51 which is in turn connected to two motor/pickoffs 53 and 54 each of which is capable of sensing the position of and driving the lower leg portion 45 about one of two mutually orthogonal axes. Within each of the motor/pickoffs 53 and 54 there is contained a position sensing device capable of producing an output signal indicative of the angular rotation of lower leg portion 45 about one of the two mutually orthogonal axes.

Motor/pickoff 53 has an output shown by a line with reference numeral 57 which leads to the processor 30 to provide positional information and processor 30 is shown having an output 59 which leads to the input of motor/pickoff 53 so as to cause the motor to drive in a prescribed fashion as directed by the processor 30. Processor 30 also has a program input 60 which is used to characterize the motor driving in accordance with the particular operator's "feel" requirements. Similarly the position sensing device within motor/pickoff 54 operates to produce an output signal indicative of the rotation of lower arm portion 45 about the other of the two mutually orthogonal axes and this signal is presented on an output shown by reference numeral 61 which leads to the processor 30. Processor 30 has an output shown by a line with reference numeral 63 connected to the motor/pickoff 54 so as to cause the motor in a prescribed fashion and in accordance with the program 60.

Similarly, lower leg portion 46 is connected to a coupling 62 which is connected to two motor/pickoffs 63 and 64 each of which is capable of sensing the position of and driving the lower leg portion 46 about one of two mutually orthogonal axes. Within each of the motor/pickoffs 63 and 64 there is contained a position sensing device capable of producing an output signal indicative of the angular rotation of the lower leg portion 46 about one of the two mutually orthogonal axes. Motor/pickoff 63 has an output shown by a line with reference numeral 65 connected to processor 30. Processor 30 has an output shown by a line with reference numeral 67 which is connected to the motor portion of motor/pickoff 63 and operates to drive shaft 46 by the desired amount along the first of the mutually orthogonal directions as directed by program input 60. Motor/pickoff 64 has an output shown by a line with reference numeral 73 which leads to the processor 30 to provide a signal indicative of the motion of arm 46 about the other of the two mutually orthogonal axes about which arm 46 moves. Microprocessor 30 has an output shown, by a line with reference numeral 75 connected to the motor/pickoff 64 to drive lower leg portion 46 about the other of the two mutually orthogonal axes as directed by program input 60.

Finally, lower leg portion 47 is connected in similar fashion to a third coupling 81 which is connected to two motor/pickoffs 83 and 84 to cause motion of arm 47 about two mutually orthogonal axes. Motor/pickoff 83 has an output shown by a line with reference numeral 85 which leads to the processor 30. Processor 30 is shown producing an output along an output shown by reference numeral 87 to motor/pickoff 83 and operable to drive the arm 47 about a first of the two mutually orthogonal axes as directed by program input 60. Motor/pickoff 84 has as an output shown by a line with reference numeral 93 which leads to

the processor 30 and is indicative of the motion of arm 47 about the other of the two mutually orthogonal axes about which arm 47 moves. Processor 30 is also shown producing an output signal on a line shown by reference numeral 95 to motor/pickoff 84 operable to drive lower arm 47 about the other of the two mutually orthogonal axes as directed by program input 60.

In addition to the pickoffs contained in the motor/pickoff combinations above described, each of the three articulated arms has an additional pickoff 97, 98 and 99, respectively, connected at the pivot joints between the upper leg portions 32, 33 and 34 and the lower leg portions 45, 46 and 47 and these pickoffs produce outputs along lines shown by references numerals 100, 101 and 102, respectively, to the processor 30 in order to give processor 30 additional information about the movement of the hand grip 10 and platform 14 with respect to the base plate 49. While the pickoffs contained in the motor/pickoff combinations 53 and 54, 63 and 64 and 83 and 84 described above would be sufficient to provide the processor 30 with sufficient information to enable it to determine the motions of the hand grip 10 and platform 14 with respect to base plate 49, the program for solving the kinematic and dynamic equations of motion of the system is somewhat simplified by having the additional inputs provided by the pickoff 97, 98 and 99, respectively. In addition to the signals to processor 30 which have been thus far described, each motor 53, 54, 63, 64, 83 and 84 includes a tachometer which produces a signal indicative of the motor's speed and these signals are also presented to the processor but,for simplicity, have not been shown in Figure 1 but will be described in connection with Figure 3.

The processor 30 is programmed at input 60 to determine the desired motion of hand grip 10 in each of the six desired axes to drive the motors in the motor/pickoff combinations accordingly. The motion of hand grip 10 is not, however, frictionless since it is desired to provide the hand grip with a "feel" which is produced by forces presented to the three articulated arms from the motor/pickoff combinations above described. In other words, as the hand grip moves from a known position it is assisted in this motion, to a certain extent, by the motor/pickoff combinations but as the hand grip gets further and further from the original point the amount of force necessary to produce additional movement of the hand grip increases. In general the motion from null is normally accompanied by resistive "feel" forces applied by the motors in accordance with the curve shown in Figure 2. In Figure 2 the horizontal axis shows the motion of the hand grip 10 and platform 14 in any one of the directions from an assumed null position directly above the center of base plate 49 while the vertical axis shows the amount of resistive force necessary to provide the "feel" desired. It

will be noticed that from the null position there is a small amount of force which can be applied before there is any motion but when the motion starts, the resistive force is a relatively constantly increasing force along the line shown by reference numeral 110. When it reaches a position A, the resistive force increases slightly to position B with no significant increase in motion. This is used to provide a "detent" feel for the hand grip 10. In other words from null to point A there is a continual increase in the force felt by the operator but as soon as it reaches point A it jogs into a "detent" requiring additional force to move it again. This would be the natural feel for the equipment at that position. Beyond point B the operator can force the hand grip 10 to move further along a relatively constantly increasing resistive force line shown by reference numeral 113 to a point C. At point C no further motion is permitted and this corresponds to the absolute limit of motion of the hand grip 10. By properly programming the processor 30, the curve such as shown in Figure 2 may be modified for different ones of the directions and for different operators desires. Such modifications would usually produce different slopes to the lines 110 and 113 but would normally be in a generalized shape such as shown in Figure 2. It is, of course, possible to modify these curves to conform to any desired resistive force. For example, the detent could be eliminated or the straight line portions 110 and 113 could be curves if desired.

Figure 3 shows the block diagram of the system wherein the modified Stewart platform of Figure 1 is shown as a box 120, and the portion surrounded by dashed line 130 represents the processor 30 of Figure 1. The output 16 from the ATI sensor 12 of Figure 1 is shown on a line 132 leading to an ATI box 134. ATI box 134 is part of the force/torque sensor 12 of Figure 1 and may be included therein but is shown in Figure 3 as a separate box for producing the electrical signals representative of the forces and torques being applied by the operator in the six directions 20-25 of Figure 1. The outputs from the various pickoffs of Figure 1 along lines 57, 61, 65, 73, 85, 93, 101, 102 and 103 are represented in Figure 3 by a single line 136 leading to a box 138 labelled "Reverse Kinematics." The "Reverse Kinematics" box 138 operates on the signals from line 136 to mathematically determine the present position of the hand grip 10 and the triangular platform 14 with respect to the base plate 49 of Figure 1. These mathematics will be described hereinafter. The tachometer signals from the various motors in Figure 1 are shown on a single line 140 in Figure 3 leading to a box 142 labelled "Motor Control" which contains circuitry for controlling the start, stop and speed of the motors in accordance with the commands from the processor and the tachometer feedback signals on line 140. The motor control signals on lines 59, 63, 65, 75,

87 and 95 of Figure 1 are represented in Figure 3 by a single line 144 coming from the "Motor Control" box 142. Finally, the program input 60 of Figure 1 is shown, by way of example as coming from a pair of keyboards 146 and 148 connected respectively to an "Input & Command Process" box 150 and the ATI box 134 by lines shown with reference numerals 152 and 154.

As mentioned, the ATI box 134 produces signals representative of the forces and torques commanded by the operator through the hand control and these signals are transferred to the "Input & Command Process" box 150 by way of lines 156 (for linear forces) and 158 (for torques). Also, as mentioned, the "Reverse Kinematics" box 138 determines mathematically the current position of the upper platform 14 with respect to the lower platform 49 and this information is transferred to the "Input & Command Process" box 150 via a line 154. "Input & Command Process" box 150 operates on the information concerning the present position of the upper platform 14 with respect to the lower platform 49, the commanded forces and torques as determined by the ATI box 134 and any modifications to the resistive force produced by the keyboards 146 and 148 to determine the desired position of the upper platform 14 with respect to the lower platform 49, and sends this information to a "Forward Kinematics" box 160 via and output shown as line 162. "Forward Kinematics" box 160 operates on the input form line 162 to mathematically determine which motors should be actuated, in which direction and with what resistive force to cause upper platform 14 to get to the desired position with respect to lower platform 49. The mathematics involved will be explained hereinafter. The information from the "Forward Kinematics" box is presented to the "Motor Control" box 142 via an output shown as line 166, and as indicated above, "Motor Control" box operates the proper motors in the modified Stewart platform box 120 to produce the desire result. The various operations are accomplished in very small steps and very rapidly. The outputs from the sensors are processed and the motors are controlled about 100 time each second so that the operator does not detect the steps by feel. Continuously updating the data and re commanding the motors this rapidly allows the force stick to move to the desire position smoothly with no detectable overshoot.

The mathematical analysis performed by the "Reverse Kinematics" box 138 will now be described with reference to Figures 4a, 4b, 4c and 5.

With regard to the coordinate systems, seven separate cartesian coordinate frames are necessary in order to describe the kinematics and dynamics of the basic J-VPHC concept. Three systems are associated with the legs, one defines the base plate and one defines the

platform frame. Two additional frames to define the "virtual pivot" coordinate frames will be introduced later. These reference frames, shown in Figure 4, are described as follows:

Base Frame (S_B) - This cartesian frame (with origin at the base centroid) has the x_B axis directed toward base pivot point B1 and Z_B directed vertically downwards. Constant Vectors $\bar{R}_{B1}$, $\bar{R}_{B2}$ and $\bar{R}_{B3}$ define the leg pivot points with respect to the origin of S_B as shown in Figure 4(c).

Lower Leg Frames (S_1, S_2 and S_3) - These frames have their origins at points $\bar{R}_{B1}$, $\bar{R}_{B2}$ and $\bar{R}_{B3}$ (See Figure 5). One joint rotates the lower leg through a roll angle ϕ (i.e., ϕ_1, ϕ_2 or ϕ_3) whose axis or rotation is radial from the origin of S_B. Roll angles are zero when the leg is in the vertical plane through the axis of rotation as shown in Figure 4(b). Each lower leg is then rotated through a pitch angle Θ, as shown in Figure 4(a). Zero pitch angle occurs when lower and upper legs form a right angle. The y_{Li} (i=1, 2, 3) axes are defined as perpendicular to the plane formed by Z_{Li} and position vectors $\bar{R}_{B1}$, $\bar{R}_{B2}$ and $\bar{R}_{B3}$, respectively.

Platform Frame (S_p) - This frame has its origin at the centroid of the plane defined by the three centers of each joint. The X_p axis is directed toward the ball joint at P1 whose position vector is $\bar{r}_{p1}$, the Z_p axis is normal (downwards) to the plane. The Y_p axis is parallel to the vector $[\bar{r}_2\text{-}\bar{r}_3]$. Vectors $\bar{r}_{p1}$, $\bar{r}_{p2}$ and $\bar{r}_{p3}$ (referred to S_p) are fixed in S_p of length a_p. Ball joint locations are $\bar{R}_i$ with respect to S_B.

With regard to the Reverse Kinematics, given the nine angles $[\phi_i, \Theta_{Li}, \Theta_{Ui}]$, where i= 1,2,3 and the constant parameters L_1 and L_2 are lower and upper link lengths, R_b and r_p are the radius of the base and platform pivots and γ_1, γ_2 and γ_3 are the mounting angles of the base pivots (B_1, B_2, B_3) then the position vectors $\bar{R}_i$ in S_B of each ball joint (illustrated in Figure 3) are then given by:

Equation 1

$$\bar{R}_i = \bar{R}_{Bi} + \bar{D}_i ; i = 1,2,3$$

where $\bar{D}_i$ is the vector between $\bar{R}_{Bi}$ and its corresponding ball joint expressed in S_B coordinates. The position vector and attitude (i.e., Euler angles) of the platform relative to the base coordinate frame S_B are then obtained from $\bar{D}_i$ and $\bar{R}_{Bi}$ vectors in a direct manner. The origin of the platform coordinate frame S_p is at the centroid of the plane defined by three ball joints, the X_p axis is toward P_1 and the Y_p axis parallel to the line joining P_2 to P_3.

The position vector $\bar{R}_p$ from the base plate origin to platform origin is then given by:

Equation 2

$$R_p \equiv \frac{1}{3}\sum_{i=1}^{3}\left(\overline{R}_{Bi}+\overline{D}_i\right)=\frac{1}{3}\sum_{i=1}^{3}\overline{D}_i$$

since

$$\sum_i \overline{R}_{Bi} \equiv 0$$

Here $\overline{D}_i$ (i = 1,2,3) are the vectors from each leg mounting location on the base (B_1, B_2, B_3) to their respective ball joints (P_1, P_2, P_3) as shown in Figure 3(a).

Coordinate frames S_1, S_2 and S_3 are obtained by first rotating S_B about the Z_B axis by 0°, -120°, and 120°, respectively, then a roll rotation ϕ_i about the resulting X_{Bi} axes (Shown in Figure 3(c). The geometry for all three legs is identical and is shown in Figure 3.

With respect to the reverse kinematics computations, in each coordinate system (S_1, S_2, S_3) the location of the ball joint relative to the base pivot point can be expressed as

Equation 3

$$\overline{D}_i = \begin{bmatrix} (L_1\cos\theta_{Li} - L_2\sin\theta_{Ui}) \\ 0 \\ (L_i\sin\theta_{Li} + L_2\cos\theta_{Ui}) \end{bmatrix}_{S_i}$$

where Θ_{Li} and Θ_{Ui} are the two joint angles of the i^{th} leg. The three vectors, $\overline{D}_i$, when transformed into S_B coordinates are given by

Equation 4

$$\left.\begin{aligned} \overline{D}_1 &= E_1^T \cdot E(\phi_1)^T \cdot \overline{D}_1|_{S1} \\ \overline{D}_2 &= E_2^T \cdot E(\phi_2)^T \cdot \overline{D}_2|_{S2} \\ \overline{D}_3 &= E_3^T \cdot E(\phi_3)^T \cdot \overline{D}_3|_{S3} \end{aligned}\right\}$$

where

Equation 5

In the above equations C() and S() represent sine and cosine functions. Rotation matrices $E(\phi)$, E_1, E_2 and E_3 represent rotations from S_B to S_i. As a result, matrix transpose

$$E(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\phi & S\phi \\ 0 & -S\phi & C\phi \end{bmatrix}; E_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$E_2 = \begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 1 \end{bmatrix}; E_3 = \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\ -\frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

is used to form the inverse transformation (denoted by superscript T). Note that the subscript i is dropped for the $E(\phi_i)$ expression (for simplification of these expressions).

the process is then determined by first computing the following vectors:

Equations 6, 7, 8

The overall process to find the position of vector $\bar{R}_p$ of the platform origin then consists of the following:

Step 1-Compute Ball Joint Position

From the nine measured shaft angles ϕ_i, θ_{Li}, and θ_{Ui} (i = 1,2,3). Compute the vectors $\bar{D}_i$ from leg base to P_i as follows:

First, compute the vectors shown above as Equations 6, 7, 8.

Second, compute $\bar{R}_p$, $\bar{R}_1$, $\bar{R}_2$, $\bar{R}_3$ vectors to the platform origin S_p and ball joints by

$$\bar{R}_p = \frac{1}{3}\sum_{i=1}^{3} \bar{D}_i$$

Equation 9

where

$$\overline{D}_1 = \begin{bmatrix} [L_1\, C\theta_{L1} - L_2\, S\theta_{U1}] \\ S\theta_1[L_1\, S\theta_{L1} + L_2\, C\theta_{U1}] \\ -C\theta[L_1\, S\theta_{L1} + L_2\, C\theta_{U1}] \end{bmatrix}$$

$$\overline{D}_2 = \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\ -\frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\phi_2 & -S\phi_2 \\ 0 & S\phi_2 & C\phi_2 \end{bmatrix} \begin{bmatrix} [L_1\; C\theta_{L2} - L_2\; S\theta_{U2}] \\ 0 \\ -[L_1\; S\theta_{L2} + L_2\; C\theta_{U2}] \end{bmatrix}$$

$$\overline{D}_3 = \begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\phi_3 & S\phi_3 \\ 0 & -S\phi_3 & C\phi_3 \end{bmatrix} \begin{bmatrix} [L_1\; C\theta_{L3} - L_2\; S\theta_{U3}] \\ 0 \\ -[L_1\; S\theta_{L3} + L_2\; C\theta_{U3}] \end{bmatrix}$$

$$\overline{R}_1 = \overline{R}_{B1} + \overline{D}_1$$

$$\overline{R}_2 = \overline{R}_{B2} + \overline{D}_2$$

$$\overline{R}_3 = \overline{R}_{B3} + \overline{D}_3$$

Equation 10

$$\overline{R}_{B1} = \begin{bmatrix} a_B \\ 0 \\ 0 \end{bmatrix}; \overline{R}_{B2} = \begin{bmatrix} -\frac{1}{2}a_B \\ -\left(\frac{\sqrt{3}}{2}\right)a_B \\ 0 \end{bmatrix}; \overline{R}_{B3} = \begin{bmatrix} -\frac{1}{2}a_B \\ \left(\frac{\sqrt{3}}{2}\right)a_B \\ 0 \end{bmatrix}$$

Step 2- Euler Rotation Matrix

The radius from platform center to ball joints is a_p. Then unit vectors in S_p are given by

Equation 11

$$\hat{X}_p = \left(\frac{1}{a_p}\right)\left[\bar{R}_1 - \bar{R}_p\right]$$

$$\hat{y}_p = \left(\frac{1}{\sqrt{3}a_p}\right)\left[\bar{R}_3 - \bar{R}_2\right]$$

$$\hat{Z}_p = \hat{X}_p x \hat{y}_p$$

The three $\hat{X}_B$, $\hat{Y}_B$, $\hat{Z}_B$ components (of each unit vector $\hat{X}_p$, $\hat{Y}_p$, $\hat{Z}_p$) are the direction cosines and form the rows of the Euler rotation matrix $E_{p/B}$ (from S_B to S_p). That is:

Equation 12

$$E_{p/B} \equiv \begin{bmatrix} (\hat{X}_p \cdot \hat{X}_B) & (\hat{X}_p \cdot \hat{y}_B) & (\hat{X}_p \cdot \hat{Z}_B) \\ (\hat{y}_p \cdot \hat{X}_B) & (\hat{y}_p \cdot \hat{y}_B) & (\hat{y}_p \cdot \hat{Z}_B) \\ (\hat{Z}_p \cdot \hat{X}_B) & (\hat{Z}_p \cdot \hat{y}_B) & (\hat{Z}_p \cdot \hat{Z}_B) \end{bmatrix}$$

Step 3 - Compute Euler Angles

All attitude information needed to define the orientation between S_B and S_p frames is given by $E_{p/B}$ and its transpose. Many differing sets of Euler angles are used in the literature, and no one set is better as (if correctly applied in sequence) they each result in the same finite rotation. One set is commonly used in the aerospace industry and involves successive yaw rotation (ψ) about the $\hat{Z}_B$ axis, then pitch (θ) about the new $\hat{Y}$ axis, and finally roll (ϕ) about the final $\hat{X}$ axis. In matrix form, this Euler matrix is given by:

Equation 13

$$E_{p/B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi & s\phi \\ 0 & -s\phi & c\phi \end{bmatrix} \begin{bmatrix} c\theta & 0 & -s\theta \\ 0 & 1 & 0 \\ s\theta & 0 & c\theta \end{bmatrix} \begin{bmatrix} c\psi & s\psi & 0 \\ -s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

or

Equation 14

$$E_{p/B} = \begin{bmatrix} C\theta C\psi & C\theta S\psi & -S\theta \\ [s\phi s\theta c\psi - c\phi s\psi] & [s\phi s\theta s\psi + c\phi c\psi] & s\phi c\theta \\ [C\phi s\theta c\psi + s\phi s\psi] & [c\phi s\theta s\psi - s\phi s\psi] & c\phi c\theta \end{bmatrix}$$

From inspection,

Equation 15

$$\left.\begin{aligned} \textbf{Roll } \phi_p &= \tan^{-1}[e_{23}/e_{33}] \\ \textbf{Pitch } \theta_p &= \sin^{-1}[-e_{13}] \\ \textbf{Yaw } \psi_p &= \tan^{-1}[e_{12}/e_{11}] \end{aligned}\right\}$$

Hence, the above computations can be applied to compute roll-pitch-yaw angles from the equations computed previously. Note that with the Euler rotation matrix between any two frames, the above Euler angle equations refer to the base frame. This will be of use later when offset frames from S_p or S_B are introduced for the virtual pivot concept.

The forward kinematics transformation assumes that the platform position vector $\bar{R}_p$ and the Euler angles are known for some future time instant. A new problem is then to compute the six shaft angles θ_{Li}, ϕ_i (i = 1,2,3) necessary to achieve the desired $\bar{R}_p$, ϕ_p, θ_p, ψ_p values.

This task is solved in two steps. First, the Euler matrix $E^*_{p/B}$ (corresponding to new values $\bar{R}^*_p$, ϕ^*_p, θ^*_p, ψ^*_p, is computed. This process is independent of the desired translation. Second, the mechanism is assumed to produce the desired translation and attitude change. The position of each mid-joint is computed as the intersection of two circles (in the plane of each leg) with the radius L_1 and L_2 centered on base pivots and ball joints, respectively.

Step 1 - Compute Future Euler Matrix

This matrix is computed from the previously given equation (14)(and denoted as $E^{*}_{p/B}$) from the desired values $\bar{R}^{*}_{p}$, ϕ^{*}_{p}, θ^{*}_{p}, ψ^{*}_{p} obtained from the control law process.

Step 2 - Compute Roll Shaft Angles

Assume that the new platform position vector is defined by Figure 4 and force inputs, i.e.

Equation 16

$$\bar{R}^{*}_{p} = \begin{bmatrix} X^{*}_{p} \\ Y^{*}_{p} \\ Z^{*}_{p} \end{bmatrix}_{B}$$

The location of the balls joints (in S_p) is obtained from

Equation 17

$$\bar{r}_{p1} = \begin{bmatrix} a_p \\ 0 \\ 0 \end{bmatrix}; \bar{r}_{p2} = \begin{bmatrix} -\frac{1}{2}a_p \\ -\left(\sqrt{\frac{3}{2}}\right)a_p \\ 0 \end{bmatrix}; \bar{r}_{p3} = \begin{bmatrix} -\frac{1}{2}a_p \\ \left(\sqrt{\frac{3}{2}}\right)a_p \\ 0 \end{bmatrix} \text{in } S_p$$

where a_p is the radial distance from the platform frame's origin.

Then,

Equation 18

$$\left.\begin{aligned} \bar{R}^{*}_{1} &= \left(\bar{R}^{*}_{p} + E^{*T}_{p/B} \cdot \bar{r}_{p1}\right)_{B}; \bar{D}^{*}_{1} = \left(\bar{R}^{*}_{1} - \bar{R}_{B1}\right) \\ \bar{R}^{*}_{2} &= \left(\bar{R}^{*}_{p} + E^{*T}_{p/B} \cdot \bar{r}_{p2}\right)_{B}; \bar{D}^{*}_{2} = \left(\bar{R}^{*}_{2} - \bar{R}_{B2}\right) \\ \bar{R}^{*}_{3} &= \left(\bar{R}^{*}_{p} + E^{*T}_{p/B} \cdot \bar{r}_{p3}\right)_{B}; \bar{D}^{*}_{3} = \left(\bar{R}^{*}_{3} - \bar{R}_{B3}\right) \end{aligned}\right\}$$

Rotating vectors $\bar{D}^{*}_{i}$ into respective S_i is accomplished by the following process which yields

ϕ_i:

Equation 19

$$\left.\begin{array}{l} \overline{D}_1^*|_{B1} = \overline{D}_1^* \Rightarrow \phi_1^* = \sin^{-1}\left[y_1/D_1^*\right] \\ \overline{D}_2^*|_{B2} = E_2\overline{D}_2^* \Rightarrow \phi_2^* = \sin^{-1}\left[y_2/D_2^*\right] \\ \overline{D}_e^*|_{B3} = E_3\overline{D}_3^* \Rightarrow \phi_3^* = \sin^{-1}\left[y_3/D_3^*\right] \end{array}\right\}$$

since X and Z components lie in the plane of each joined leg. Here, D^*_i = $\left[X_i^2 + y_i^2 + Z_i^2\right]^{\frac{1}{2}}$.

Step 3 - Compute Joint Position

Computing $\cos\phi_i$ = $\left[1 - \left(y_i^*/D_i^*\right)^2\right]^{\frac{1}{2}}$ eases the computation of $E\left(\phi_i^*\right)$ which enables

Equation 20

$$\overline{D}_i^*|_{Si} = E\left(\phi_i^*\right)\left\{E_i\overline{D}_i^*\right\} = \begin{bmatrix} a \\ o \\ b \end{bmatrix}_{Si}$$

The equations for the two circles are

Equation 21

$$\left.\begin{array}{r} (X-a)^2 + (Z-b)^2 = L_2^2 \\ X^2 + Z^2 = L_1^2 \end{array}\right\}$$

These equations have two solutions which define the two intersections shown in Figure 4. The desired solution for the joint coordinates X^*_J and Z^*_J is:

Equation 22

$$\left.\begin{aligned} X_j^* &= a\left[1+\left(\frac{L_1^2-L_2^2}{R^2}\right)\right]+b\left[\frac{L_1^2}{R_2}-\frac{1}{4}\left\{1+\left(\frac{L_1^2-L_2^2}{R^2}\right)\right\}^2\right]^{\frac{1}{2}} \\ Z_j^* &= \frac{b}{2}\left[1-\frac{a^2}{b^2}\right]\left[1+\left(\frac{L_1^2-L_2^2}{R_2}\right)\right]-\frac{a}{2R}\left[4L_1^2-R^2\left\{1+\left(\frac{L_1^2-L_2^2}{R^2}\right)\right\}^2\right]^{\frac{1}{2}} \end{aligned}\right\}$$

where

$$R = [a^2+b^2]^{\frac{1}{2}}$$

If links L_1,L_2 for each leg are all of equal length, the above equations reduce to:

Equation 23

$$\left.\begin{aligned} X_j^* &= a+b\,\frac{\left[\left(\frac{L}{R}\right)^2-\frac{1}{4}\right]^{1}}{2} \\ Z_j^* &= \frac{b}{2}\left(1-\frac{a^2}{b^2}\right)-\frac{a}{2R}\,[4L^2-R^2]^{\frac{1}{2}} \end{aligned}\right\}$$

Step 4 - Compute Leg Shaft Angles

Having completed the previous step, the lower shaft angle θ^*_{Li} for each leg is given by:

Equation 24

$$\theta^*_{Li} = \tan^{-1}\left(-X^*_{Ji}/Z^*_{JI}\right);\, i = 1,2,3$$

where $\left(X_i^*, Z_i^*\right)$ are the solutions to the three sets of quadratic equations (with the largest positive X-root). The passive leg segments L_2 (which are driven by L_1) have angles

Equation 25

$$\theta^*_{Ui} = \sin^{-1}\left[\left(X^*_{Ji}a_L\right)/L^2\right];\, i = 1,2,3$$

Note that values outside of

Equation 26

$$0 \langle\ \theta_{Ui} \langle \frac{\pi}{4}$$

denote a serious problem as the jointed leg segment will pass through a toggle configuration if this occurs. At the completion of this computational step, the six shaft angles ϕ^*_{Li}, ϕ^*_i (i - 1,2,3) are output to the shaft-angle motor drive controller.

Virtual Pivot Modification

The patented virtual pivot concept described in the above mentioned U.S. Patent 4,962,448, when applied to the kinematics described earlier, requires use of two additional coordinate frames, i.e.:

i. Relative-to-Platform System (S_v) - defined by a fixed offset vector $\bar{r}_{Vp}$ from S_p to S_v and an Euler rotation matrix E_{Vp}. This frame translates with S_p and may be defined at the center of an operator's wrist joint; and

ii. Relative to Base System (S_{VB}) - defined by an offset position vector $\bar{R}_{Vb}$ which is fixed and does not translate with S_p.

It is assumed that a logic discrete selects the appropriate virtual pivot system (or none at all). The default is the absence of any. The utility of S_{VB} is in its ability to simulate floor or ceiling mounted operator-sensed pivot points. The unique ability of S_{Vp} is to move the sensed pivot point to the center of the operator's wrist (for example) and thereby decouple translation and gap attitude commands.

Modifications to the kinematics are as follows:

1. The measured position vector of the platform is changed to the measured position at the virtual pivot origin, i.e.

Equation 27

$$\overline{R}_v = \overline{R}_p + \left(E_{Vp} E_{p/B}\right)^T \bar{r}_{Vp} \text{ for } S_{Vp}$$

or

Equation 28

2. Euler angles are computed from

$$\overline{R}_v = \left(\overline{R}_{VB} - \overline{R}_{p}\right) \text{ for } S_{VB}$$

Equation 29

$$E_{V/B} = \left(E_{VP} \cdot E_{p/B}\right) \text{ for } S_{Vp}$$

It is therefore seen that I have provided a six-degree-of-freedom hand controller which operates with motorized resistance and applied proper resistive force so as to provide a correct "feel" and in which no motor is require to drive the weight of another motor. Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A six-degree-of-freedom controller comprising:

first and second platforms (14,49) spaced apart by first, second and third articulated legs (32-45,33-46,34-47) each having a first end (35; 36,37) pivotally attached to the first platform, a second end (51; 62,81) pivotally connected to the second platform and moveable about first and second mutually perpendicular axes;

hand controller means (10) mounted on the first platform and operable to respond to a force applied by a controller's hand in a desired direction to produce first signals indicative thereof;

first and second motive means (53-54,63-64,83-84) connected to the second end of each leg and operable in response to input control signals to move the second ends in directions which will allow motion of the hand controller in the desired direction and provide enough resistance to the force applied by the controllers hand to give the proper "feel" to the operation of the hand controller;

sensing means (53-54,63-64,83-84) attached to the second end of each leg and operable to sense motion about first and second mutually perpendicular axes; and,

processor means (30) connected to receive the signals from the sensing means and from the hand controller and to modify them by a characterized amount predetermined according to the operator's desires and to supply the modified signals to the first and second motive means as the input control signals.

2. Apparatus according to claim 1 further including means (60) associated with the processor means to provide the information necessary for the processor to perform the characterization of the signals in accordance with the operator's desires.

3. Apparatus according to claim 2 wherein the further means is programmed for the desires of each individual operator.

4. Apparatus according to claim 1 further including pivot means (40,41,42) between

the first and second ends of each articulated leg and pivot sensing means (97,98,99) to supply additional signals indicative of the amount of pivot of each pivot means to the processor means, the processor means using the additional signals with the signals from the hand controller and the sensing means to produce the input control signals.

5. Apparatus according to claim 4 further including means (60) associated with the processor means to provide the information necessary for the processor to perform the characterization of the signals in accordance with the operator's desires.

6. Apparatus according to claim 5 further including pivot means (40,41,42) between the first and second ends of each articulated leg and pivot sensing means (97,98,99) to supply additional signals indicative of the amount of pivot of each pivot means to the processor means, the processor means using the additional signals with the signals from the hand controller and the sensing means to produce the input control signals.

7. Apparatus according to claim 1 wherein the signals from the hand controller are indicative of linear forces along three mutually perpendicular axes and indicative of rotational torques about three mutually perpendicular axes.

8. Apparatus according to claim 7 wherein the processor means includes a reverse kinematics circuit (138) to receive the signals from the sensing means and produce an output in accordance the present position of the second ends of the articulated legs about the two axes associated therewith;

a force responsive circuit (134) to receive the signals from the hand controller and to produce an output in accordance with the linear forces and rotational torques from the hand controller;

processing circuitry (150) operable in accordance with the outputs from the reverse kinematics circuit and the force responsive circuit to characterize the signals and produce an output (162) in accordance with the operator's desires; forward kinematics circuit (160) to receive the output from the processing circuitry and produce signals (166) indicative of the desired motion of the second ends of the articulated legs about the two mutually perpendicular axes and motor control circuit (142) receiving the output of

the forward kinematics circuit and to produce the input control signal (144) to the first and second motive means for each articulated leg.

9. Apparatus according to claim 8 further including a tachometer (53-54,63-64,83-84) for each first and second motive means operable to provide a feedback signal (140) to the motor control circuit.

10. Apparatus according to claim 9 further including means (60) associated with the processor means to provide the information necessary for the processor to perform the characterization of the signals in accordance with the operator's desires.

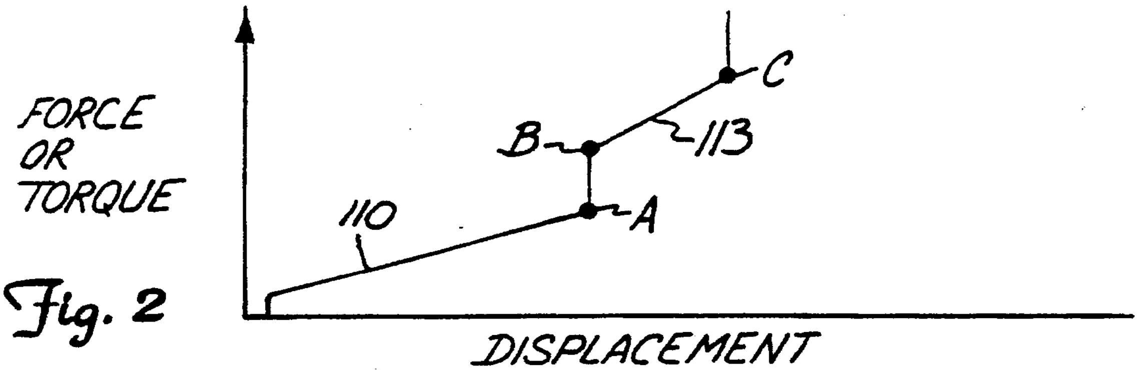
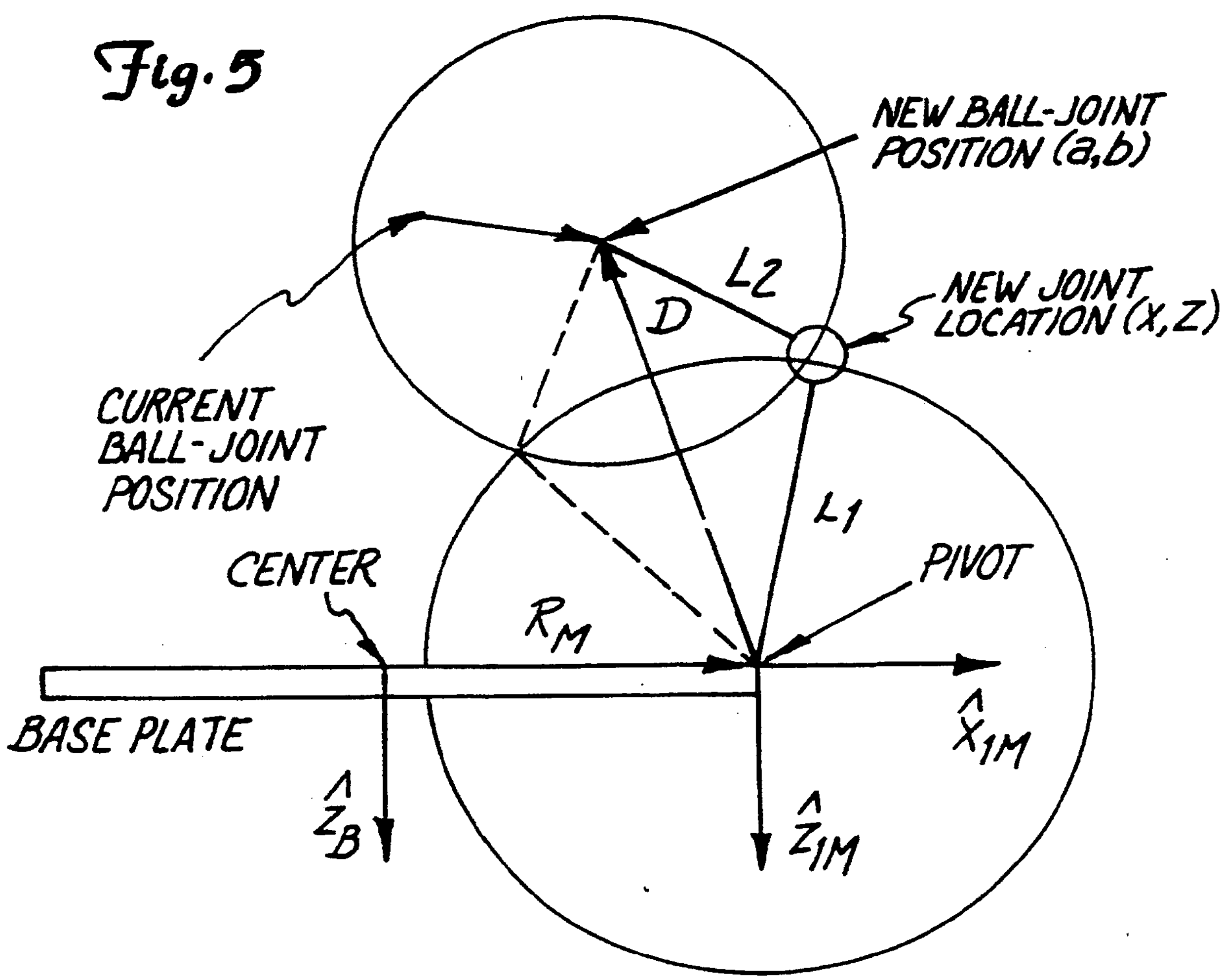
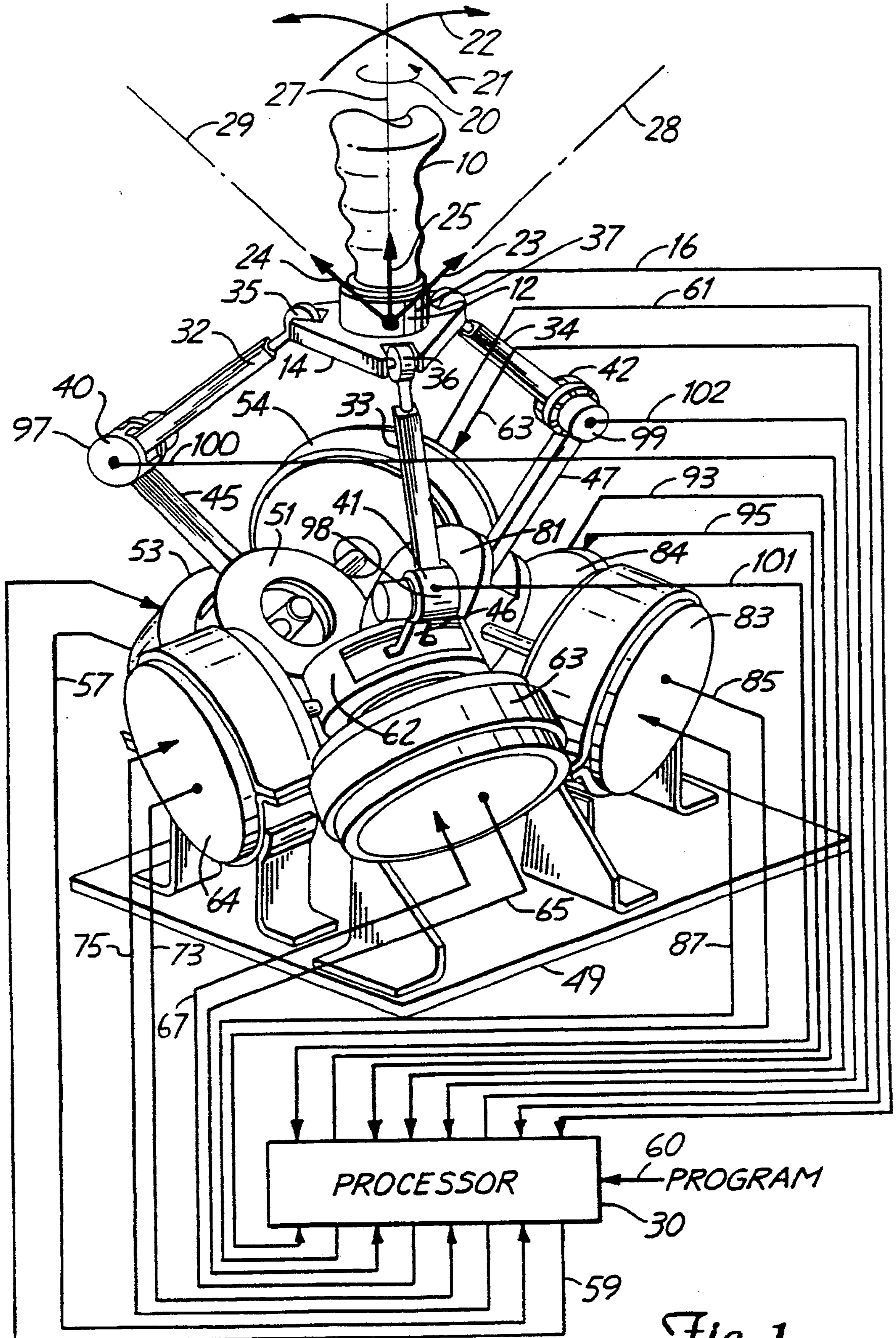

FORCE
OR
TORQUE
DISPLACEMENT
110
A
B
C
113

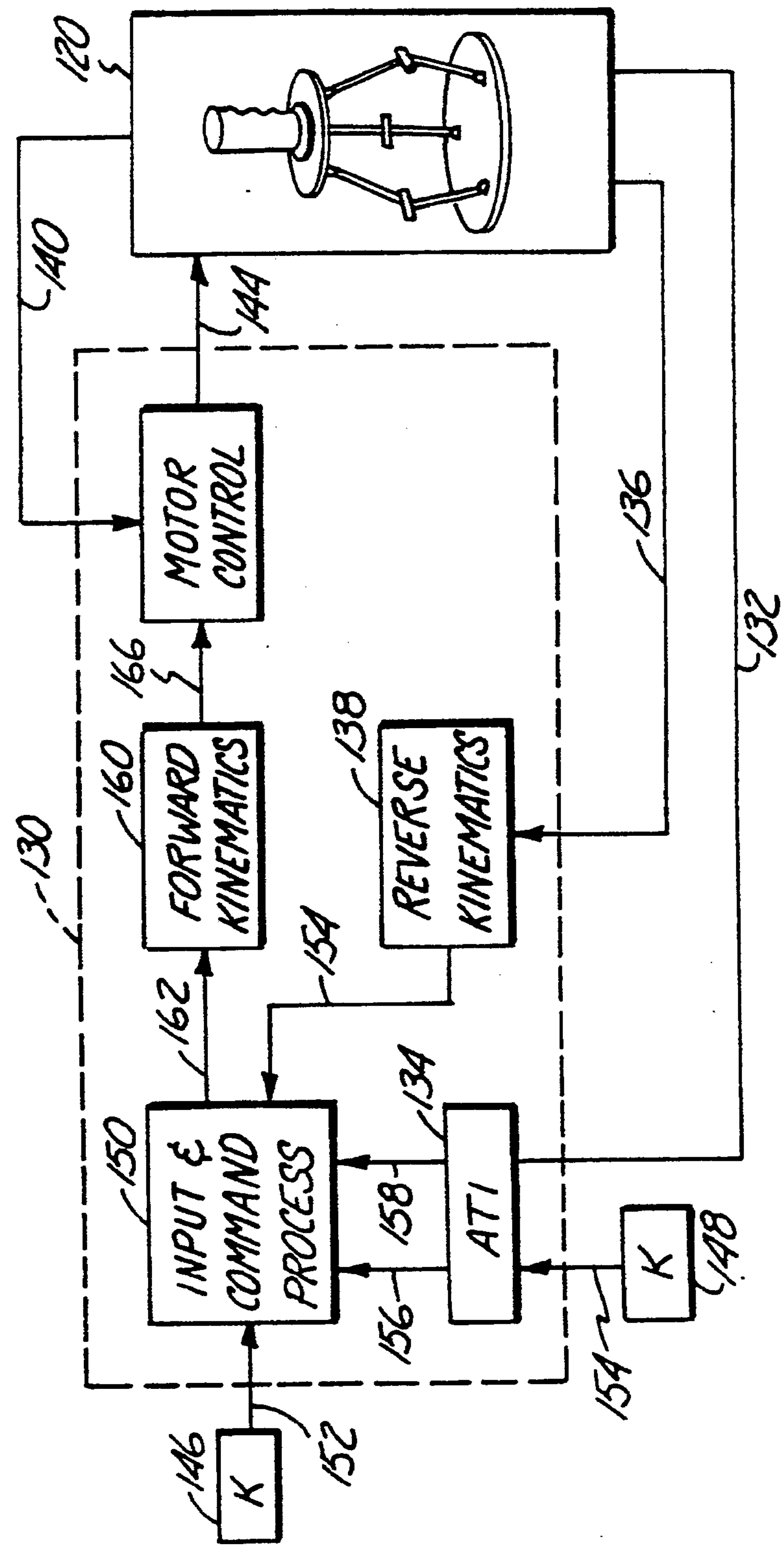
Fig. 2

Fig. 5


NEW BALL-JOINT
POSITION (a,b)
L2
D
NEW JOINT
LOCATION (X,Z)
CURRENT
BALL-JOINT
POSITION
L1
CENTER
PIVOT
RM
BASE PLATE
X1M
ZB
Z1M



SUBSTITUTE SHEET Fig 1


MOTOR CONTROL
FORWARD KINEMATICS
REVERSE KINEMATICS
INPUT & COMMAND PROCESS
ATI
K
K
120
140
144
136
132
166
160
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146
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Fig.3

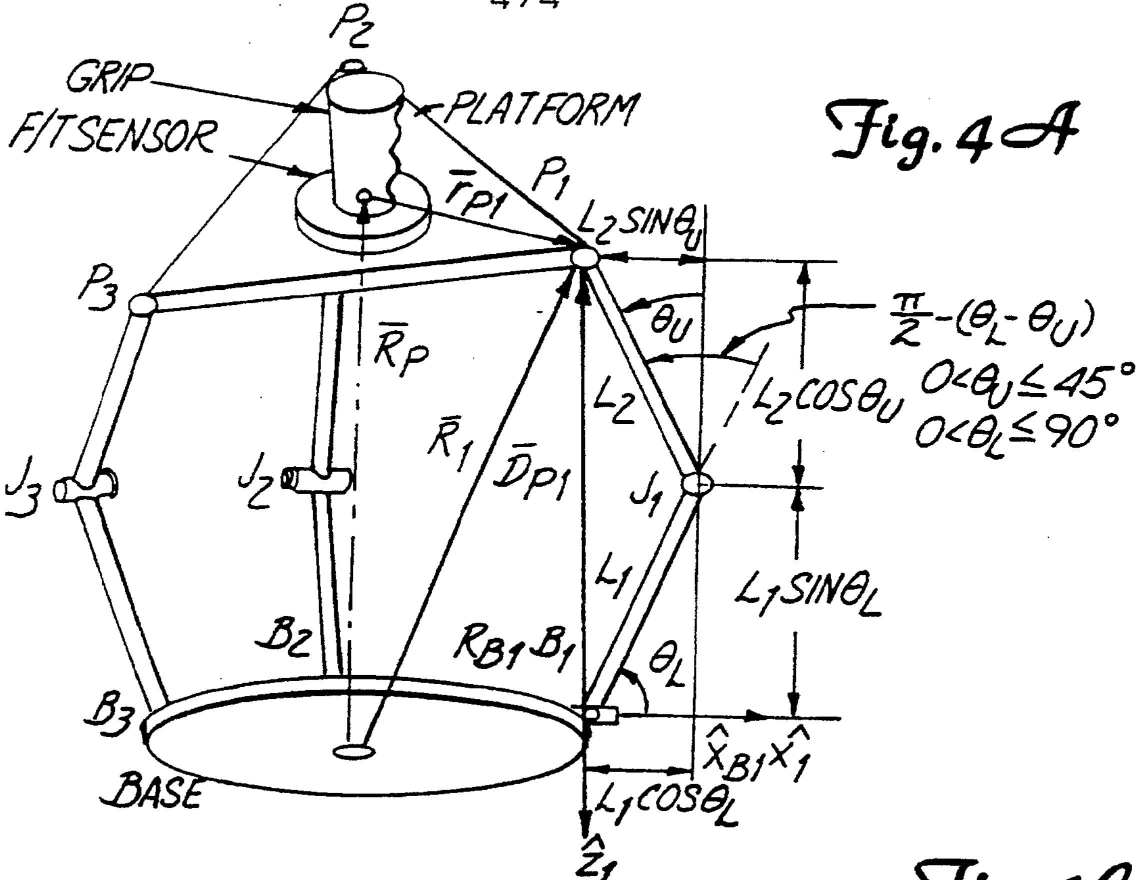

Fig. 4A

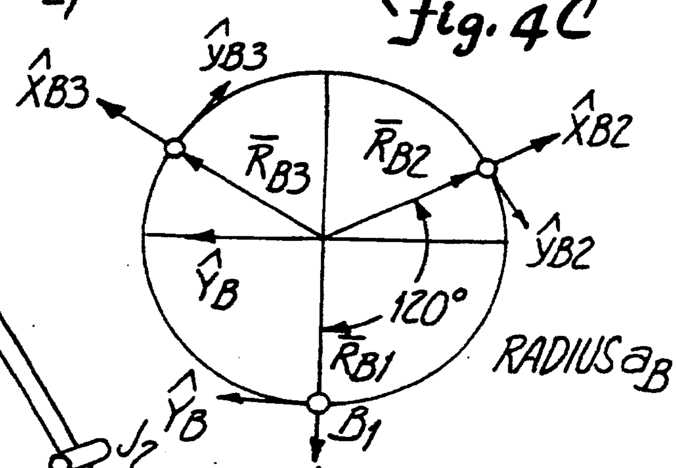

Fig. 4C

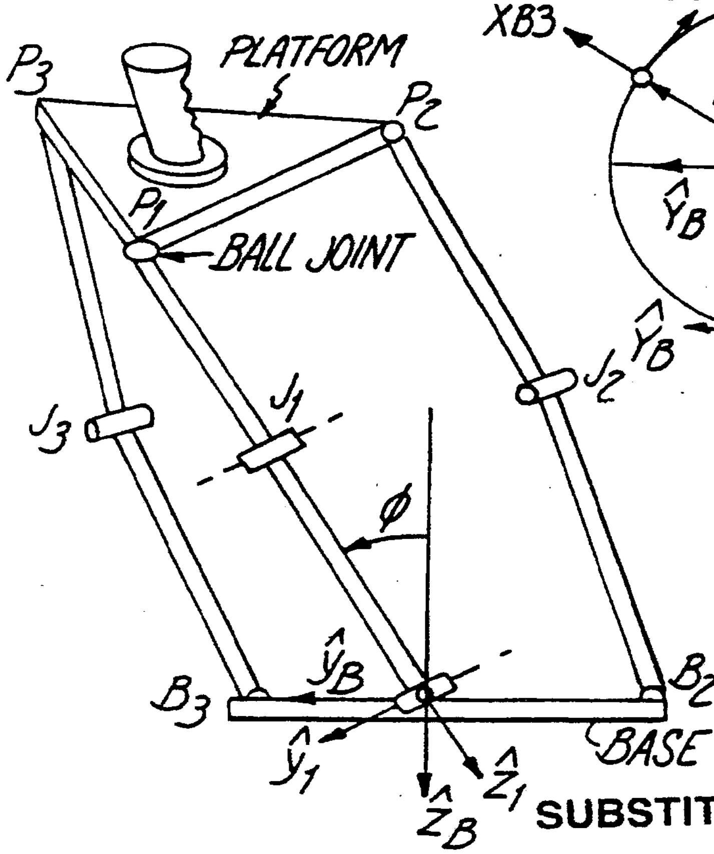

Fig. 4B

SUBSTITUTE SHEET

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 93/07469

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G05G9/047 B25J13/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G05G B64C G06K B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP,A,0 493 795 (HONEYWELL) 8 July 1992 cited in the application see page 4, line 32 - line 51; figure 1 ---	1
A	GB,A,2 228 783 (UNITED KINGDOM ATOMIC ENERGY AUTHORITY) 5 September 1990 see page 1, line 3 - line 7 see page 1, line 20 - page 2, line 30 see page 4, line 3 - page 5, line 10; figures 1,2 -----	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
6 April 1994	20.04.94

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Zeri, A

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US 93/07469

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP-A-0493795	08-07-92	US-A-	5223776	29-06-93
		JP-A-	5073150	26-03-93
GB-A-2228783	05-09-90	DE-A-	4005343	06-09-90
		US-A-	5007300	16-04-91